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A study of the distortion of holes due to bending of structural steel

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A STUDY OF THE DISTORTION OF HOLES DUE TO BENDING OF STRUCTURAL STEEL

by

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A STUDY OF THE DISTORTION OF HOLES DUE TO BENDING OF STRUCTURAL STEEL

C. Ravindranath

ABSTRACT

Structural Steel angles are often bent for fabricating various structures, mainly towers. A number of holes have to be punched, often near the bend, primarily as bolt holes. It would be desirable, for ease in production, to punch these holes before bending. Unfortunately, the holes distort by various degrees (depending on conditions of bending) when the angle is bent. In most cases, however, (especially bolt holes) a certain amount of distortion can be tolerated. It would be useful to know the amount of distortion that can be expected under a given set of conditions. There is no method at present to predict whether a hole at a certain distance from a bend will distort. Industries use various trial and error methods or rules of thumb. Therefore, it would be useful to have a method to predict the distortion so that a decision could be made to punch the hole before or after bending. The latter would mean higher production costs because of extra handling.

The object of this thesis was to study the distortion of holes under various conditions, and to investigate the possibility of finding a method to predict whether a hole would distort or not given the size of the structural angle, distance of the hole from the bend and the degree of bend.

Two experiments were done and it was found that the significant factors that caused distortion within the range

considered were:

1) Degree of bend

2) Distance of edge of hole from bend line

3) Width of leg containing hole.

Regression equations were then established for the distortions along the maximum and minimum diameters.

INTRODUCTION

The study was undertaken at the Lehigh Structural Steel Co., Allentown, Pa. which is a large steel fabricating firm.

It was found that no previous research had been done in this field. This is supported by the following structural firms and agencies who were contacted for any information on the subject:

1) Bethlehem Steel Co.
2) Bethlehem Corporation
3) Bethlehem Fabricators
4) Lehigh Structural Steel Co.
5) Westinghouse Electric Corporation
6) American Iron & Steel Institute
7) American Society of Civil Engineers
8) American Society of Mechanical Engineers
9) American Metal Stamping Association

In addition various handbooks, Structural steel books and Technical Papers were reviewed with no success.

It was decided to conduct the whole study experimentally without taking into consideration the theoretical aspects of stress concentration, or the change in metallurgical structure due to distortion.

In structural steel fabrication there are four types of bends to be considered. They are:

1) <u>Knee Bend</u>
   - (a) Up Bend
   - (b) Down Bend
2) <u>Hip Bend</u>
   - (a) Up Bend
   - (b) Down Bend

These types of bends are shown in Figure 1. In addition, for all these types of bends, the angle may be bent hot or cold, depending on the degree of bend.

This study will be limited to cold bends. The only type of bend considered in this study will be the Up Knee Bend because it is the most common type of bend used. The material chosen was A36 structural steel (Bethlehem Steel), as this is the most common structural steel material. The experiments were conducted under shop conditions, using bending machinery that is used for daily production purposes. The holes were punched on a punching press, and bent using V dies. The bending was done manually. The length of the angles, for all the experiments was 2ft $\pm$ 1/16in.

The range of values for the independent variables was chosen from the conditions usually encountered in structural steel fabrication. The fact that all the bending was done cold, limited the ranges to some extent. The maximum range possible for cold bends was taken for each variable.

The first experiment was conducted to find out the significant independent variables. The independent variables considered were:

1) Degree of bend
2) Distance of hole from bend line
3) Distance of hole from heel of structural angle
4) Thickness of material
5) Width of the leg containing the hole
6) Width of opposite leg

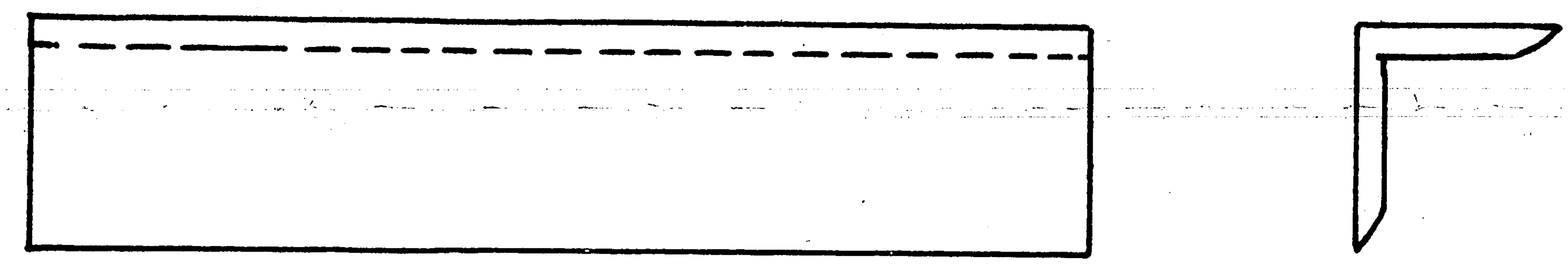
The dependent variable taken was the distortion.

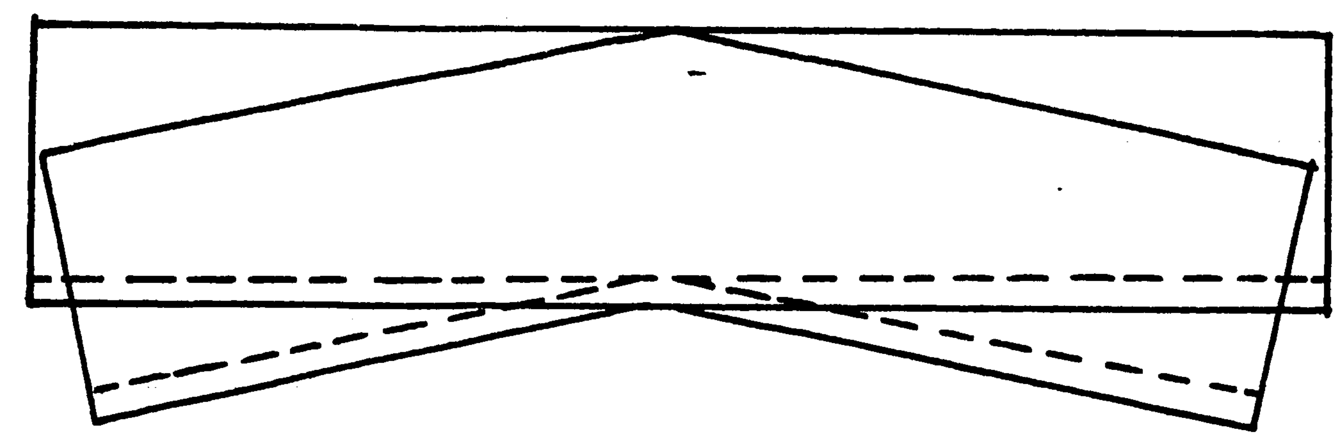
The independent variables chosen for the second experiment were those that were found statistically significant in the first experiment, with hole distortion as the dependent variable.

Fig. 1

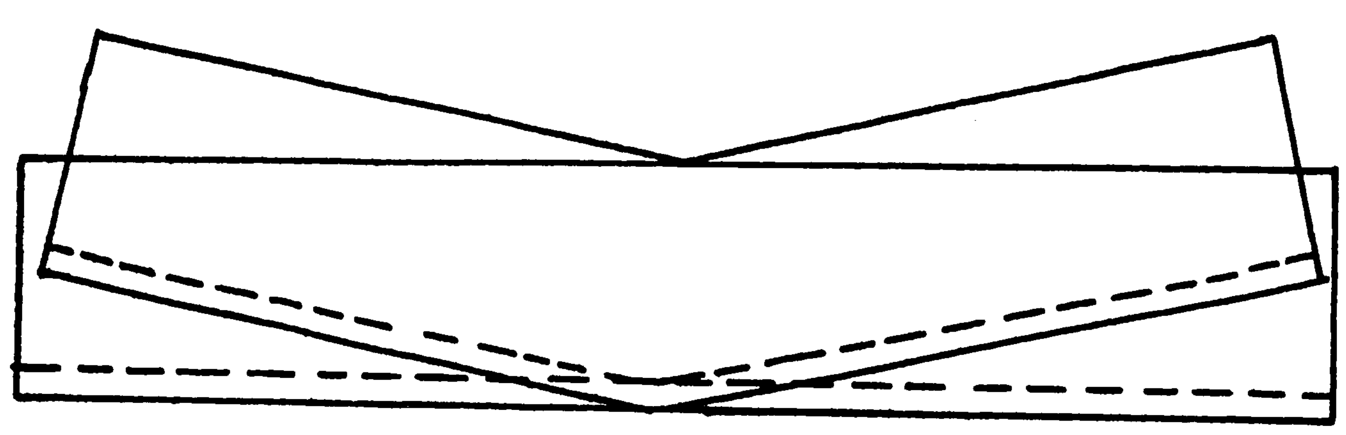
TYPES OF BENDS

1) Knee Bend



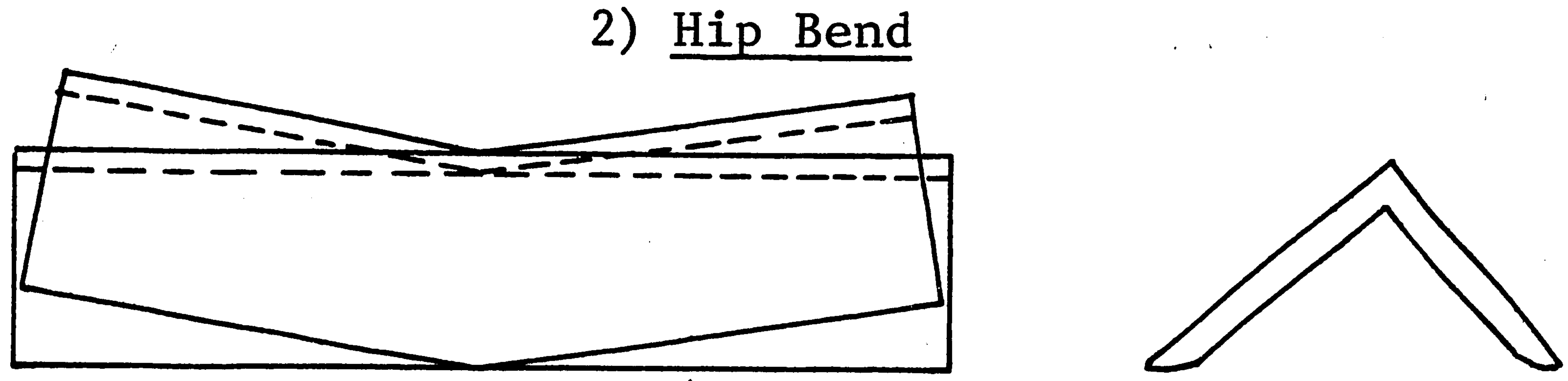


(a) Up Bend

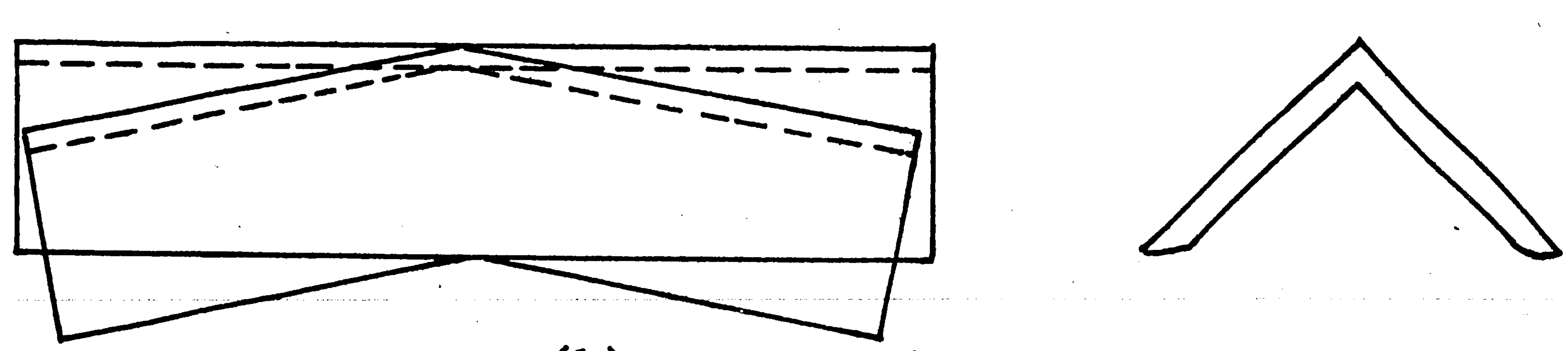


(b) Down Bend

2) Hip Bend



(a) Up Bend



(b) Down Bend

EXPERIMENT 1

Object

The object of this experiment was to find the significant variables that affect distortion. This was so as to design the main experiment taking into consideration only the significant variables. Thus, this experiment was designed to find the significant main effects.

Equipment

A punch press was used for punching the holes. The angles were bent manually using a press with V dies to suit the degree of bend. The distortion was measured using Vernier calipers accurate to .001in. A rough sketch of the press is shown in Fig.2.

Description of the Experiment

The independent variables considered in this experiment were:

1) A Degree of bend
2) B Distance of edge of hole from bend line
3) C Distance of edge of hole from heel of angle
4) D Thickness of material
5) E Width of leg containing hole
6) F Width of opposite leg

The distances of the holes from the bend line and heel of the angle were taken from the edge of the hole instead of from the center so as to eliminate the size of the hole as an independent variable.

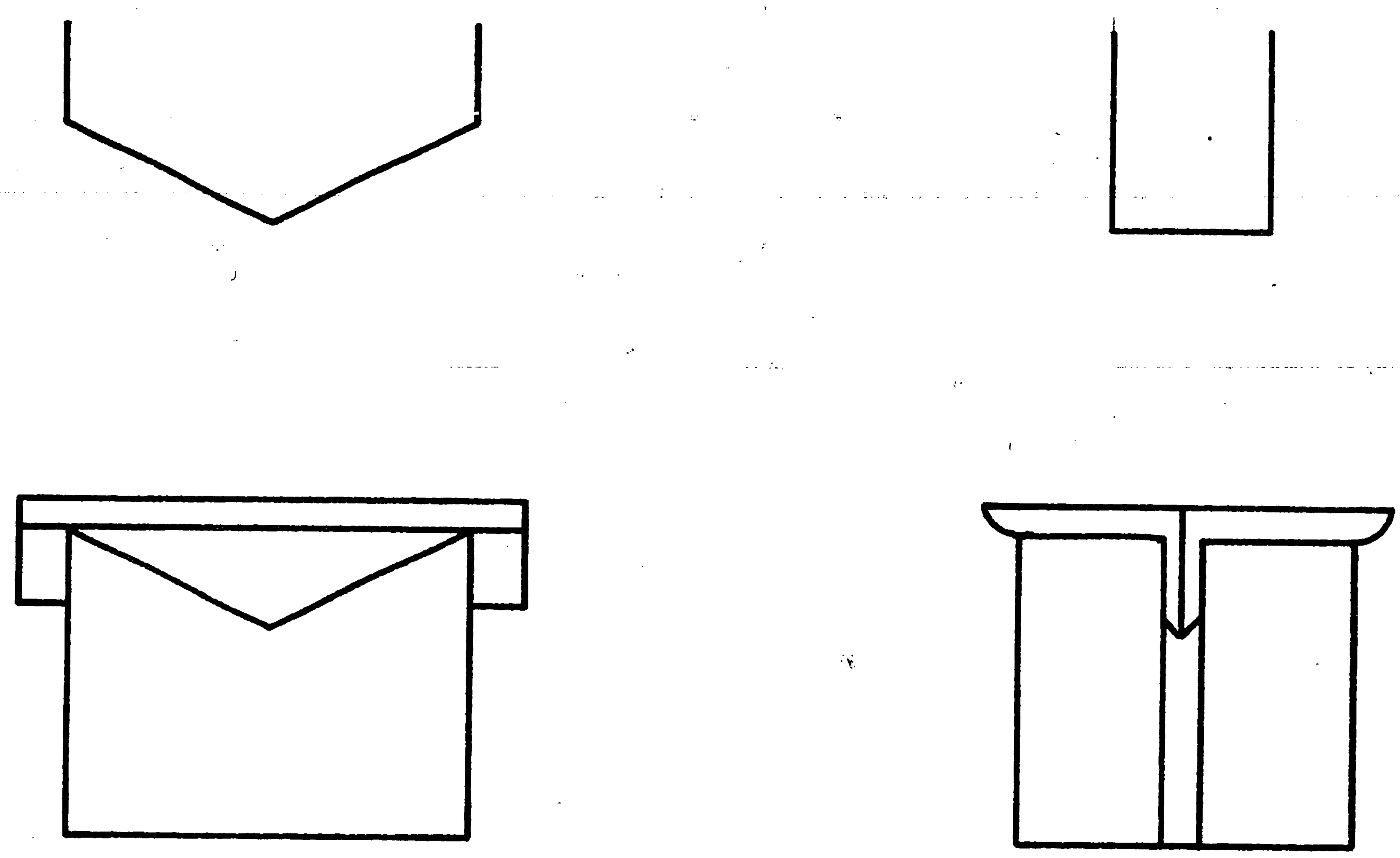
The dependent variable considered was the hole distortion. As a round hole becomes oval-shaped after distortion, the distortion was measured in terms of the maximum diameter and the minimum diameter. In the former case the distortion was taken as [(maximum diameter)-(original diameter)] and in the

Fig.2 **ROUGH SKETCH SHOWING PRESS USED FOR BENDING**

Punch

Angles to be bent

Die



FRONT VIEW

SIDE VIEW

NOTE: Two angles with equal degrees of bend were bent together. If there was only one angle with a certain degree of bend, to be bent, then a scrap piece was used.

latter case as [(original diameter)-minimum diameter)]. All holes were measured before and after bending.

The ranges were defined for each variable from the values most commonly used in Structural steel fabrication, and limited by cold bending. The two extreme values in each range were taken for this initial experiment.

The object of this first experiment was to design the smallest experiment possible so as to give the significant main effects and then to design another experiment with more levels of these variables determined as significant factors. A $\frac{1}{4} \times 2^6$ experiment was designed with each of the 6 factors, at two levels, the high and the low levels. The main effects were confounded with third order and fourth order interactions. The significance of the first order interactions could not be judged conclusively because they had to be confounded with other first order interactions.

The levels of the factors were as follows:

A_0 = 1 in 12	A_1 = 4 in 12
B_0 = 1in.	B_1 = 2ins.
C_0 = 5/8in.	C_1 = 13/16in.
D_0 = 3/16in.	D_1 = 3/8in.
E_0 = 2ins.	E_1 = 3ins.
F_0 = 2ins.	F_1 = 3ins.

All the angles were cut to 2ft lengths.

Two holes were punched for each condition, one on each side of the bend line and the distortions were added for each reading. This was done to eliminate any possible error in measurement, and also in the distances due to the tolerances involved.

DESIGN OF EXPERIMENT

Design of $\frac{1}{4} \times 2^6$ Experiment

			A_0				A_1			
			B_0		B_1		B_0		B_1	
			C_0	C_1	C_0	C_1	C_0	C_1	C_0	C_1
D_0	E_0	F_0	(1) 1						ab 2	
		F_1				bcf 3		acf	4	
	E_1	F_0				bce 5		ace 6		
		F_1	ef 7						abef 8	
D_1	E_0	F_0		cd 9						abcd 10
		F_1			bdf 11		adf 12			
	E_1	F_0			bde 13		ade 14			
		F_1		cdef 15						abcdef 16

RESULTS & ANALYSIS

After the holes were punched, all the distances involved were measured. Most of the measurements were found to be within .01in. of the conditions prescribed. The highest variation was found to be .04in.

The distortions measured in each case are given below:

Table E.1.1

Data for $\frac{1}{4} \times 2^6$ Experiment

		Sum of max. dia. - orig. dia. for two cases	Sum of orig. dia. - min. dia. for two cases
1	(1)	+ .049	- .005
2	ab	+ .091	+ .023
3	bcf	+ .021	+ .006
4	acf	+ .346	+ .039
5	bce	+ .027	+ .009
6	ace	+ .152	+ .107
7	ef	+ .049	+ .037
8	abef	+ .055	+ .041
9	cd	+ .075	- .016
10	abcd	+ .113	- .020
11	bdf	+ .060	- .041
12	adf	+ .176	+ .052
13	bde	+ 0	+ .008
14	ade	+ .112	+ .104
15	cdef	+ .027	+ .017
16	abcdef	+ .063	+ .052

The analysis of variance was performed from the data in Table E.1.1 and given hereafter. All the main effects, a few first order interactions, and a couple of second order interactions are shown. All the other interactions have been confounded. The details of the derivation of the analysis of variance table are given in Appendix I. Separate analyses have been done for the maximum diameter and the minimum diameter.

Analysis of Variance for Maximum Diameter

Table E.1.2

Source of Variation	Effect	Degrees of Freedom	Sum of Squares
A	+ .800	1	20×10^{-3}
B	- .556	1	9.6×10^{-3}
C	+ .232	1	1.7×10^{-3}
D	- .164	1	0.8×10^{-3}
E	- .446	1	6.2×10^{-3}
F	+ .178	1	1.0×10^{-3}
AB	- .372	1	4.3×10^{-3}
AC	+ .248	1	1.9×10^{-3}
AD	- .196	1	1.2×10^{-3}
AE	- .242	1	1.8×10^{-3}
AF	+ .166	1	0.9×10^{-3}
CE	- .126	1	0.5×10^{-3}
ACE	- .162	1	0.8×10^{-3}
CF	+ .002	1	$.000125 \times 10^{-3}$
ACF	+ .230	1	1.6×10^{-3}

Analysis of Variance for Minimum Diameter

Table E.1.3

Source of Variation	Effect	Degrees of Freedom	Sum of Squares
A	+ .383	1	46×10^{-4}
B	- .257	1	21×10^{-4}
C	- .025	1	0.2×10^{-4}
D	- .101	1	3×10^{-4}
E	+ .337	1	36×10^{-4}
F	- .007	1	0.015×10^{-4}
AB	- .155	1	8×10^{-4}
AC	- .059	1	1×10^{-4}
AD	+ .057	1	1×10^{-4}
AE	+ .083	1	2×10^{-4}
AF	- .053	1	0.88×10^{-4}
CE	+ .015	1	0.07×10^{-4}
ACE	+ .125	1	5×10^{-4}
CF	+ .075	1	2×10^{-4}
ACF	+ .001	1	$.0003 \times 10^{-4}$

DISCUSSION OF RESULTS

For the maximum diameter, by examining the last column of Table E.1.2 it is found that the greatest sources of variation are A, B and E i.e. the degree of bend, the distance of the edge of the hole from the bend line and the width of the leg containing the hole. The other main effects, namely C, D and E (distance of edge of hole from heel of angle, thickness of material and the width of the opposite leg) are insignificant compared to these. No inferences can be made at this point about the significance of the interactions because they are confounded with other equal-order interactions.

Similarly, for the minimum diameter, by examining Table E.1.3, it is found that the greatest sources of variation are again A, E and B. The other main effects are not significant compared to these.

It was concluded that within the range considered in this experiment, the significant factors were, the degree of bend, the distance of the edge of the hole from the bend line and the width of the leg containing the hole. Therefore, these factors will be studied more closely in the next experiment.

EXPERIMENT 2

Object

It was concluded from the previous experiment that the significant factors affecting the distortion of holes were the degree of bend, the distance of the hole from bend line and the width of the leg containing the hole within the range considered. The object of this experiment was to study these factors closely and to examine the significance of their first order interactions and to possibly establish a regression equation for the degree of hole distortion.

Equipment

The equipment for punching, bending and measuring distortion was the same as for the last experiment.

Description of the Experiment

The independent variables taken in this experiment were the ones that were found significant in the last experiment. They were:

A Degree of bend

B Distance of edge of hole from bend line

C Width of the leg containing hole

A 5 x 4 x 3 factorial experiment was designed and a complete replicate was done. The levels of the various factors were as follows:

A	1/12	2/12	3/12	4/12	
B	1-11/32in.	1-19/32in.	1-27/32in.	2-3/32ins.	2-11/32ins.
E	2in.	2½ins.	3ins.		

The dependent variable was the hole distortion as before, which was taken along the maximum and minimum diameters. Once again distortion was measured as (maximun diameter - original diameter) for the maximum diameter, and (original diameter - minimum diameter) for the minimum diameter.

The range taken for the independent variables was the same as that taken for the last experiment. Two holes were punched, one on each side of the bend line for each condition, and the sum of the distortions was taken for each cell of the experiment.

The other three factors considered in the previous experiment were kept fixed, the distance of the edge of the hole from the heel at 1-1/8in., and the thickness of material at ¼in. and the width of the opposite leg at 2½ins.

DESIGN OF 5 x 3 x 4 EXPERIMENT

	A_0 1/12			A_1 2/12			A_2 3/12			A_3 4/12		
	E_0 2"	E_1 2½"	E_2 3"	E_0 2"	E_1 2½"	E_2 3"	E_0 2"	E_1 2½"	E_2 3"	E_0 2"	E_1 2½"	E_2 3"
1-11/32" B_0	17	18	19	20	21	22	23	24	25	26	27	28
1-19/32" B_1	29	30	31	32	33	34	35	36	37	38	39	40
1-27/32" B_2	41	42	43	44	45	46	47	48	49	50	51	52
2-3/32" B_3	53	54	55	56	57	58	59	60	61	62	63	64
2-11/32" B_4	65	66	67	68	69	70	71	72	73	74	75	76

A Degree of bend
B Distance of edge of hole from bend
E Width of leg with hole
C Distance of edge of hole from heel fixed at 1-1/8"
D Thickness of material fixed at ¼"
F Width of opposite leg fixed at 2½"

RESULTS & ANALYSIS

Table E.2.1 gives the distortion along the maximum diameter for each of the holes on either side of the bend line and also the sum of the distortions of the two holes for each condition.

Table E.2.2 gives the same data measured along the minimum diameter.

The analyses of variance for the two cases are shown on Tables E.2.3 (maximum diameter) and E.2.4 (minimum diameter). Appendix 2 shows how these tables were arrived at from Tables E.2.1 and E.2.2.

Table E.2.1 **DATA FOR 5 x 3 x 4 EXPT. (MAX. DIA.)**

No.	First Hole			Second Hole			Sum of Distortions
	Orig. Dia.	Dia. after bending	Dist-ortion	Orig. Dia.	Dia. after bending	Dist-ortion	
17	.666	.693	.027	.662	.694	.032	.059
18	.673	.694	.021	.673	.701	.028	.049
19	.671	.691	.020	.663	.700	.037	.057
20	.668	.736	.068	.672	.730	.058	.126
21	.671	.723	.052	.673	.730	.057	.109
22	.673	.715	.042	.673	.720	.047	.089
23	.675	.744	.069	.666	.763	.097	.166
24	.674	.733	.059	.675	.756	.081	.140
25	.664	.752	.088	.664	.726	.052	.140
26	.668	.804	.136	.676	.746	.070	.206
27	.673	.770	.097	.668	.754	.086	.183
28	.676	.766	.090	.667	.740	.073	.163
29	.673	.688	.015	.673	.686	.013	.028
30	.669	.692	.023	.671	.685	.014	.037
31	.671	.687	.016	.665	.686	.021	.037
32	.671	.722	.051	.666	.732	.066	.117
33	.670	.721	.051	.673	.711	.038	.089
34	.669	.712	.043	.672	.715	.043	.086
35	.674	.738	.064	.672	.752	.080	.144
36	.673	.730	.057	.661	.735	.074	.131
37	.668	.730	.062	.666	.722	.056	.118
38	.669	.784	.115	.663	.756	.093	.208
39	.675	.757	.082	.672	.738	.066	.148
40	.674	.741	.067	.661	.738	.077	.144
41	.669	.684	.015	.663	.704	.041	.056
42	.673	.683	.010	.673	.688	.015	.025
43	.674	.683	.009	.663	.692	.029	.038
44	.663	.718	.045	.663	.723	.060	.105
45	.675	.708	.033	.673	.708	.035	.068
46	.673	.708	.035	.675	.711	.036	.071
47	.666	.720	.054	.667	.735	.068	.122
48	.670	.709	.039	.670	.713	.043	.082
49	.676	.705	.029	.676	.711	.035	.064
50	.667	.768	.101	.669	.748	.079	.180
51	.672	.729	.057	.669	.734	.065	.122
52	.676	.721	.045	.676	.716	.040	.085
53	.667	.690	.023	.673	.688	.015	.038
54	.673	.680	.007	.668	.683	.015	.022
55	.675	.676	.001	.672	.682	.010	.011

No.	First Hole			Second Hole			Sum of Distortions
	Orig. Dia.	Dia. after bending	Dist-ortion	Orig. Dia.	Dia. after bending	Dist-ortion	
56	.665	.703	.038	.669	.718	.049	.087
57	.673	.699	.026	.675	.700	.025	.051
58	.675	.698	.023	.674	.721	.047	.070
59	.673	.732	.059	.671	.709	.038	.097
60	.673	.696	.023	.672	.706	.034	.057
61	.672	.711	.039	.667	.700	.033	.072
62	.673	.733	.060	.666	.748	.077	.137
63	.667	.709	.042	.673	.723	.050	.092
64	.670	.702	.032	.668	.722	.054	.086
65	.673	.683	.010	.669	.688	.019	.029
66	.674	.683	.009	.673	.683	.010	.019
67	.676	.672	- .004	.672	.675	.003	- .001
68	.667	.693	.026	.669	.710	.041	.067
69	.674	.692	.018	.672	.692	.020	.038
70	.671	.694	.023	.675	.701	.026	.049
71	.674	.720	.046	.674	.700	.026	.072
72	.673	.702	.029	.671	.702	.031	.060
73	.675	.688	.013	.675	.696	.021	.034
74	.675	.729	.054	.665	.722	.057	.111
75	.674	.719	.045	.672	.706	.034	.079
76	.673	.696	.023	.672	.712	.040	.063

Table E.2.2 DATA FOR 5 x 3 x 4 EXPT. (MIN. DIA.)

No.	First Hole			Second Hole			Sum of Distortions
	Orig. Dia.	Dia. after bending	Dist-ortion	Orig. Dia.	Dia. after bending	Dist-ortion	
17	.666	.666	.000	.662	.677	- .015	- .015
18	.673	.676	- .003	.673	.670	.003	.000
19	.671	.651	.020	.663	.658	.005	.025
20	.668	.654	.014	.672	.662	.010	.024
21	.671	.659	.012	.673	.653	.020	.032
22	.673	.639	.034	.673	.646	.027	.061
23	.675	.654	.021	.666	.650	.016	.037
24	.674	.652	.022	.675	.644	.031	.053
25	.664	.632	.032	.664	.648	.016	.048
26	.668	.646	.022	.676	.650	.026	.048
27	.673	.600	.073	.668	.634	.034	.107
28	.676	.620	.056	.667	.634	.033	.089
29	.673	.677	- .004	.673	.667	.006	.002
30	.669	.670	- .001	.671	.674	- .003	- .004
31	.671	.666	.005	.665	.662	.003	.008
32	.671	.658	.013	.666	.662	.004	.017
33	.670	.646	.024	.673	.661	.012	.036
34	.669	.640	.029	.672	.645	.027	.056
35	.674	.657	.017	.672	.654	.018	.035
36	.673	.638	.035	.661	.652	.009	.044
37	.668	.640	.028	.666	.653	.013	.041
38	.669	.644	.025	.663	.643	.020	.045
39	.675	.635	.040	.672	.642	.030	.070
40	.674	.626	.048	.661	.640	.021	.069
41	.669	.677	- .008	.663	.667	- .004	- .012
42	.673	.676	- .003	.673	.663	.010	.007
43	.674	.663	.011	.663	.659	.004	.015
44	.663	.666	- .003	.663	.664	- .001	- .004
45	.675	.669	.006	.673	.665	.008	.014
46	.673	.643	.030	.675	.647	.028	.058
47	.666	.659	.007	.667	.657	.010	.017
48	.670	.651	.019	.670	.659	.011	.030
49	.676	.649	.027	.676	.651	.025	.052
50	.667	.652	.015	.669	.654	.015	.030
51	.672	.644	.028	.669	.646	.023	.051
52	.676	.649	.027	.676	.654	.022	.049
53	.667	.679	- .012	.673	.673	.000	- .012
54	.673	.664	.009	.668	.674	- .006	.003
55	.675	.670	.005	.672	.662	.010	.015

No.	First Hole			Second Hole			Sum of Distortions
	Orig. Dia.	Dia. after bending	Dist-ortion	Orig. Dia.	Dia. after bending	Dist-ortion	
56	.665	.654	.011	.669	.670	- .001	.010
57	.673	.675	- .002	.675	.676	- .001	- .003
58	.675	.652	.023	.674	.644	.030	.053
59	.673	.644	.029	.671	.664	.007	.036
60	.673	.660	.013	.672	.658	.014	.027
61	.672	.652	.020	.667	.658	.009	.029
62	.673	.658	.013	.666	.654	.012	.025
63	.667	.644	.023	.673	.656	.017	.040
64	.670	.661	.009	.668	.646	.022	.031
65	.673	.675	- .002	.669	.675	- .006	- .008
66	.674	.675	- .001	.673	.673	.000	.001
67	.676	.668	.008	.672	.656	.016	.024
68	.667	.667	.000	.669	.671	- .002	- .002
69	.674	.671	.003	.672	.672	.000	.003
70	.671	.651	.020	.675	.653	.022	.042
71	.674	.659	.015	.674	.679	- .005	.010
72	.673	.664	.009	.671	.663	.008	.017
73	.675	.654	.021	.675	.658	.017	.038
74	.675	.653	.022	.665	.668	- .003	.019
75	.674	.643	.031	.672	.654	.018	.049
76	.673	.665	.008	.672	.660	.012	.020

ANALYSIS OF VARIANCE (maximum dia.)

Table E.2.3

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Variance Ratio
Between levels of				
Factor A	.0392965	3	.0130988	99.22 *
Factor B	.0202448	4	.0050612	38.34 *
Factor E	.0065298	2	.0032649	24.73 *
Interactions AB	.0012900	12	.00010242	0.78
AE	.0015900	6	.00026500	2.01 ¢
BE	.0005727	8	.00007159	0.54
Remainder = Interaction ABE	.0031685	24	.00013202	
TOTAL	.0726925	59		

* Significant at 99% level

¢ Significant at 90% level

ANALYSIS OF VARIANCE (minimum dia.)

Table E.2.4

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Variance Ratio
Between levels of				
Factor A	.0084026	3	.00280087	108.77 *
Factor B	.0025000	4	.00062500	24.27 *
Factor E	.0031457	2	.00157285	61.08 *
Interactions AB	.0016472	12	.00013727	5.33 *
AE	.0020189	6	.00033648	13.07 *
BE	.0006760	8	.00008450	3.29 ¢
Remainder = Interaction ABE	.0006180	24	.00002575	
TOTAL	.0190097	59		

* Significant at 99%

¢ Significant at 95%

A regression analysis was done based on Tables E.2.1 and E.2.2. The computer outputs using a Multiple Linear Regression Program package are shown below. The details are described in Appendix 3.

LINEAR REGRESSION FOR DISTORTION ALONG MAXIMUM DIAMETER

FIT IS FORCED THROUGH MEAN

SUMMARY OF REGRESSION FOR DEPENDENT VARIABLE = V 01

R **2[MAXIMUM LIKELIHOOD] .87974022 00

R **2[BASED ON UNBIASED VARIANCES] .87329773 00

RESIDUAL MS = .78269580-04

VAR.	NO.	FIT THROUGH	COEFFICIENT	S.D. COEFF.
A	02	.20832500 00	.19145594 00	.12259266-01
B	04	.18438000 01	-.36683293-01	.32304698-02
C	03	.25000000 01	-.16974989-01	.27976700-02

F[**2]	CONF. LVL
.24389831 03	3
.12894522 03	3
.36815106 02	3

CONSTANT TERM = .11378907 00

LINEAR REGRESSION FOR DISTORTION ALONG MINIMUM DIAMETER

FIT IS FORCED THROUGH MEAN

SUMMARY OF REGRESSION FOR DEPENDENT VARIABLE = V 01

R **2[MAXIMUM LIKELIHOOD] .73012504 00

R **2[BASED ON UNBIASED VARIANCES] .71566745 00

RESIDUAL MS = .45834567-04

VAR.	NO.	FIT THROUGH	COEFFICIENT	S.D. COEFF.
A	02	.20832500 00	.88088102-01	.93813324-02
E	03	.25000000 01	.13025001-01	.21409008-02
B	04	.18438000 01	-.12683326-01	.24720984-02

F[**2]	CONF. LVL
.88166877 02	3
.37013691 02	3
.26322965 02	3

CONSTANT TERM = -.13361273-01

CONCLUSIONS

1. It is found from experiment 1 that the significant variables affecting distortion, within the range considered, are:

   a) Degree of bend

   b) Distance of edge of hole from bend line

   c) Width of leg containing hole

2. The results given above are confirmed in the second experiment. It is also found that for the maximum diameter, the interaction between the degree of bend and the width of the leg containing the hole is almost significant at the 90% level.

3. For the minimum diameter the interactions between the degree of bend and the distance of edge of hole from bend line and between the degree of bend and width of leg containing the hole are significant at the 99% level. The interaction between the distance of the edge of the hole from the bend line and the width of the leg containing the hole is significant at the 95% level.

4. The regression equation for the distortion along the maximum diameter is:

$$\text{Distortion in inches} = \text{Maximum diameter} - \text{original diameter}$$

$$= 0.19145594A - 0.036683293B - 0.016974989E + .11378907$$

where

A = degree of bend expressed as tangent of angle

B = distance of edge of hole from bend line in inches

E = width of leg containing hole in inches

5. The regression equation for the distortion along the minimum diameter is:

$$\text{Distortion in inches} = \text{original diameter} - \text{minimum diameter}$$

$$= .088088102A - .012683326B + .013025001E - .013361273$$

where

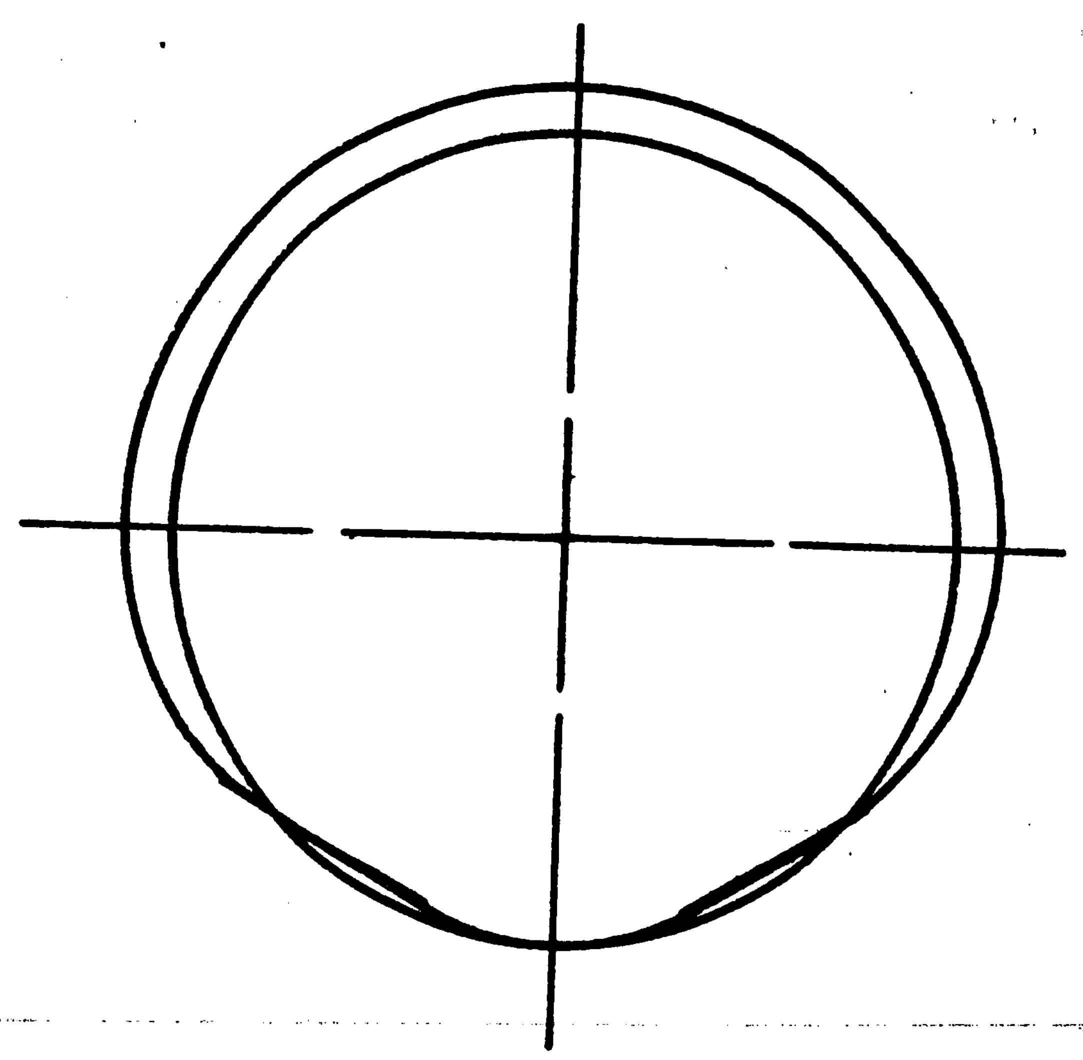
A = degree of bend expressed as tangent of angle

B = distance of edge of hole from bend line in inches

E = width of leg containing hole in inches

DISCUSSION OF CONCLUSIONS

It is found from the tables containing the measured distortions that under some conditions both the maximum and minimum diameters are greater than the original diameter. This can be explained by the fact that most of the holes after distortion are egg-shaped, and it is conceivable that one half of the hole could expand in all directions while the other half narrows down as shown below:



It is interesting to note that for the distortion measured along the maximum diameter only one of the interactions is significant whereas in the case of the minimum diameter all the interactions are significant. An analysis of the reasons for this would require a study of the stress concentration which is not within the scope of this paper.

Since, in the regression analysis for the distortion along the maximum diameter, R^2 = .8797, the goodness of fit is pretty good, and the linear equation is a good representation of the distortion. The confidence level of 3 for all the factors indicates that they are significant at the 99%

confidence level. In the case of the minimum diameter R^2 = .7301 and the goodness of fit is fairly good.

It is feasible that this distortion can be overcome by making non circular holes, making allowances for the distortion along the maximim and minimum diameters, so that the distorted hole would become round. The only problem here is that the holes are not oval but egg-shaped. Also, it is difficult to determine the axes along which the maximum and minimum diameters would lie, because it was found in the experiment that the axes did not lie in the same direction for each case.

RECOMMENDATIONS FOR FUTURE STUDY

1. Establish a formula for the bend allowances necessary when bending structural steel. Various structural firms have charts of allowances for different bends and conditions. These charts have been made by trial rather than by any methodical way.

2. Establish the limits for cold bending for various types of bends. Here again charts have been made by trial rather than theoretical research.

3. Extend the regression equation discussed in this study to other ranges of conditions.

4. Establish similar regression equations for other types of bends.

5. Study methods of predicting distortion for hot bends.

6. Test the validity of getting round holes by punching non-circular holes, with allowances made for the distortion along the maximum and minimum diameters.

APPENDIX 1

The details of the experimental design and derivation of the analysis of variance table for Experiment 1 are given below:

For this experiment with 6 factors, each at two levels, a design of size 16 arranged in 1 block was used. The defining contrasts ABCD, ABEF and then "product" CDEF were chosen. The alias-groups are given in Table 1A.

A block of 16 treatment combinations was then chosen on the basis of the 3 defining contrasts. The treatments in this block are

(1)	bce	abef	acf
ab	ace	ef	bcf
cd	bde	abcdef	adf
abcd	ade	cdef	bdf

The table of signs for calculating the main effects and interactions are given in Table 1B.

The effects and interactions were then calculated as shown in tables 1C and 1D.

The sum of squares for each source of variation was then calculated as given in Tables E.1.2 and E.1.3 by squaring the effects and dividing by 32, because each reading was the sum of the distortions of two holes, one on each side of the bend line.

ALIAS GROUPS IN THE $\frac{1}{4} \times 2^6$ EXPERIMENT
WITH DEFINING CONTRASTS ABCD, ABEF, CDEF

Effect	Aliases		
I	ABCD	ABEF	CDEF
A	BCD	BEF	ACDEF
B	ACD	AEF	BCDEF
C	ABD	ABCEF	DEF
D	ABC	ABDEF	CEF
E	ABCDE	ABF	CDF
F	ABCDF	ABE	CDE
AB	CD	EF	ABCDEF
AC	BD	BCEF	ADEF
AD	BC	BDEF	ACEF
AE	BCDE	BF	ACDF
AF	BCDF	BE	ACDE
CE	ABDE	ABCF	DF
CF	ABDF	ABCE	DE
ACE	BDE	BCF	ADF
ACF	BDF	BCE	ADE

MAIN EFFECTS AND INTERACTIONS IN 2^6 FACTORIAL DESIGN

Table 1B

Treatment Combinations	I	A	B	AB	C	AC	D	AD	E	AE	F	AF	CE	ACE	CF	ACF
									Effects							
(1)	+	−	−	+	−	+	−	+	−	+	−	+	+	−	+	−
ab	+	+	+	+	−	−	−	−	−	−	−	−	+	+	+	+
cd	+	−	−	+	+	−	+	−	+	+	+	+	−	+	−	+
abcd	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−
bce	+	−	+	−	+	−	−	+	+	−	−	+	+	−	−	+
ace	+	+	−	−	+	+	−	−	+	+	−	−	+	+	−	−
bde	+	−	+	−	−	+	+	−	+	−	−	+	−	+	+	−
ade	+	+	−	−	−	−	+	+	+	+	−	−	−	−	+	+
abef	+	+	+	+	−	−	−	−	+	+	+	+	−	−	−	−
ef	+	−	−	+	−	+	−	+	+	−	+	−	−	+	−	+
abcdef	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
cdef	+	−	−	+	+	−	+	−	+	−	+	−	+	−	+	−
acf	+	+	−	−	+	+	−	−	−	−	+	+	−	−	+	+
bcf	+	−	+	−	+	−	−	+	−	+	+	−	−	+	+	−
adf	+	+	−	−	−	−	+	+	−	−	+	+	+	+	−	−
bdf	+	−	+	−	−	+	+	−	−	+	+	−	+	−	−	+

ESTIMATED EFFECT OF CHANGES IN FACTOR LEVELS FOR MAXIMUM DIAMETER

Source of Variation	Effect
A	-(1) + ab - cd + abcd - bce + ace - bde + ade + abef - ef + abcdef - cdef + acf - bcf + adf - bdf = + .800
Similarly	
B	- .556
C	+ .232
D	- .164
E	- .446
F	+ .178
AB	- .372
AC	+ .248
AD	- .196
AE	- .242
AF	+ .166
CE	- .126
ACE	- .162
CF	+ .002
ACF	+ .230

ESTIMATED EFFECT OF CHANGES IN FACTOR LEVELS FOR MINIMUM DIAMETER

Table 1D

Source of Variation	Effect
A	-(1) + ab - cd + abcd - bce + ace - bde + ade + abef - ef + abcdef - cdef + acf - bcf + adf - bdf = + 383
Similarly	
B	- .257
C	- .025
D	- .101
E	+ .337
F	- .007
AB	- .155
AC	- .059
AD	+ .057
AE	+ .083
AF	- .053
CE	+ .015
ACE	+ .125
CF	+ .075
ACF	+ .001

APPENDIX 2

The derivation of the Analysis of Variance Tables E.2.3 and E.2.4 are given below:

Tables 2A and 2B are summaries of Tables E.2.1 and E.2.2, giving sum of the distortions of the holes along the maximum and minimum diameters.

Tables 2C, 2D, 2E, 2F, 2G and 2H are two-way tables of sums for the various factors.

Tables 2J and 2K show the calculation of the sum of squares of changes in factor levels for the maximum and minimum diameters. The Analysis of Variance Tables E.2.3 and E.2.1 were derived from these.

Table 2A DISTORTIONS OF HOLES (ALONG THE MAXIMUM DIAMETER)

	A_0 0.0833			A_1 0.1667			A_2 0.2500			A_3 0.3333			
	E_0 2	E_1 2.5	E_2 3	E_0 2	E_1 2.5	E_2 3	E_0 2	E_1 2.5	E_2 3	E_0 2	E_1 2.5	E_2 3	Totals
B_0 1.5938	17 .059	18 .049	19 .057	20 .126	21 .109	22 .089	23 .166	24 .140	25 .140	26 .206	27 .183	28 .163	1.487
B_1 1.5938	29 .028	30 .037	31 .037	32 .117	33 .089	34 .086	35 .144	36 .131	37 .118	38 .208	39 .148	40 .144	1.287
B_2 1.8438	41 .056	42 .025	43 .038	44 .105	45 .068	46 .071	47 .122	48 .082	49 .064	50 .180	51 .122	52 .085	1.018
B_3 2.0938	53 .038	54 .022	55 .011	56 .087	57 .051	58 .070	59 .097	60 .057	61 .072	62 .137	63 .092	64 .086	0.820
B_4 2.3438	65 .029	66 .019	67 -.001	68 .067	69 .038	70 .049	71 .072	72 .060	73 .034	74 .111	75 .079	76 .063	0.620
Totals	.210	.152	.142	.502	.355	.365	.601	.470	.428	.842	.642	.541	5.232

Table 2B <u>DISTORTIONS OF HOLES (ALONG THE MINIMUM DIAMETER)</u>

	A_0 0.0833			A_1 0.1667			A_2 0.2500			A_3 0.3333			
	E_0 2	E_1 2.5	E_2 3	E_0 2	E_1 2.5	E_2 3	E_0 2	E_1 2.5	E_2 3	E_0 2	E_1 2.5	E_2 3	Totals
B_0 1.3438	17 -.015	18 .000	19 .025	20 .024	21 .032	22 .061	23 .037	24 .053	25 .048	26 .048	27 .089	28 .089	0.509
B_1 1.5938	29 .002	30 -.004	31 .008	32 .017	33 .036	34 .056	35 .035	36 .044	37 .041	38 .045	39 .070	40 .069	0.419
B_2 1.8438	41 -.012	42 .007	43 .015	44 -.004	45 .014	46 .058	47 .017	48 .030	49 .052	50 .030	51 .051	52 .049	0.307
B_3 2.0938	53 -.012	54 .003	55 .015	56 .010	57 -.003	58 .053	59 .036	60 .027	61 .029	62 .025	63 .040	64 .031	0.254
B_4 2.3438	65 -.008	66 -.001	67 .024	68 -.002	69 .003	70 .042	71 .010	72 .017	73 .038	74 .019	75 .049	76 .020	0.211
Totals	-.045	.005	.087	.045	.082	.270	.135	.171	.208	.167	.317	.258	1.700

TWO-WAY TABLE OF SUMS FOR FACTORS A & B (MAX. DIA.)

Table 2C

	A_0	A_1	A_2	A_3	Sum
B_0	.165	.324	.446	.552	1.487
B_1	.102	.292	.393	.500	1.287
B_2	.119	.244	.268	.387	1.018
B_3	.071	.208	.226	.315	0.820
B_4	.047	.154	.166	.263	0.620
Sum	.504	1.222	1.499	2.007	5.232

TWO-WAY TABLE OF SUMS FOR FACTORS A & B (MIN. DIA.)

Table 2D

	A_0	A_1	A_2	A_3	Sum
B_0	.010	.117	.138	.244	1.487
B_1	.006	.109	.120	.184	0.419
B_2	.010	.068	.099	.130	0.307
B_3	.006	.060	.092	.096	0.254
B_4	.015	.043	.065	.088	0.211
Sum	.047	.397	.514	.742	1.700

TWO-WAY TABLE OF SUMS FOR FACTORS E & B (MAX. DIA.)

Table 2E

	E_0	E_1	E_2	Sum
B_0	.557	.481	.449	1.487
B_1	.497	.405	.385	1.287
B_2	.463	.297	.258	1.018
B_3	.359	.222	.239	0.820
B_4	.279	.196	.145	0.620
Sum	2.155	1.601	1.476	5.232

TWO-WAY TABLE OF SUMS FOR FACTORS E & B (MIN. DIA.)

Table 2F

	E_0	E_1	E_2	Sum
B_0	.094	.192	.223	0.509
B_1	.099	.146	.174	0.419
B_2	.031	.102	.174	0.307
B_3	.059	.067	.128	0.254
B_4	.019	.068	.124	0.211
Sum	.302	.575	.823	1.700

TWO-WAY TABLE OF SUMS FOR FACTORS E & A (MAX. DIA.)

Table 2G

	E_0	E_1	E_2	Sum
A_0	.210	.152	.142	.504
A_1	.502	.355	.365	1.222
A_2	.601	.470	.428	1.499
A_3	.842	.624	.541	2.007
Sum	2.155	1.601	1.476	5.232

TWO-WAY TABLE OF SUMS FOR FACTORS E & A (MIN. DIA.)

Table 2H

	E_0	E_1	E_2	Sum
A_0	-.045	.005	.087	.047
A_1	.045	.082	.270	.397
A_2	.135	.171	.208	.514
A_3	.167	.317	.258	.742
Sum	.302	.575	.823	1.700

Table 2J ESTIMATED SUM OF SQUARES OF CHANGES IN FACTOR LEVELS FOR MAXIMUM DIAMETER

Sum of squares due to B

$= (.1487^2 + 1.287^2 + 1.018^2 + 0.820^2 + 0.620^2)/24 - 5.232^2/120 = \underline{0.0202448}$

Sum of squares due to E

$= [(.210 + .502 + .601 + .842)^2 + (.152 + .355 + .470 + .624)^2 + (.142 + .365 + .428 + .541)^2]/40 - 5.232^2/120$

$= [(2.155)^2 + (1.601)^2 + (1.476)^2]/40 - 0.2281152 = \underline{0.0065298}$

Sum of squares due to A

$= [(.210 + .152 + .142)^2 + (.502 + .355 + .365)^2 + (.601 + .470 + .428)^2 + (.842 + .624 + .541)^2]/30 - .2281152$

$= (.504^2 + 1.222^2 + 1.499^2 + 2.007^2)/30 - .2281152 = \underline{0.0392965}$

Total sum of squares for factors A & B

$= (.165^2 + .324^2 + ... + .253)^2/6 - .2281152 = .06083$

Sum of squares due to AB

$= .06083 - .03930 - .02024 = \underline{.00129}$

Total sum of squares for factors E & B

$= (.557^2 + .481^2 + ... + .145^2)/8 - .2281152 = .0273473$

Sum of squares due to BE

$= .0273473 - .0202448 - .0065298 = \underline{.0005727}$

Total sum of squares for factors A & E

$= (.210^2 + .152^2 + ... + .541^2)/10 - .2281152 = .04741$

Sum of squares due to AE

$= .04741 - .0392965 - .0065298 = \underline{.00159}$

Total Sum of squares $= (.059^2 + .049^2 + ... + .063^2)/2 - .2281152 = \underline{.0726923}$

Table 2K **ESTIMATED SUM OF SQUARES OF CHANGES IN FACTOR LEVELS FOR MINIMUM DIAMETER**

Sum of squares due to B

$$= (0.509^2 + 0.419^2 + 0.307^2 + 0.254^2 + 0.211^2)/24 - 1.700^2/120 = \underline{.0025}$$

Sum of squares due to E

$$= [(-.045 + .045 + .135 + .167)^2 + (.005 + .082 + .171 + .317)^2 + (.087 + .270 + .208 + .258)^2]/40 - 1.700^2/120$$

$$= (.302^2 + 575^2 + .823^2)/40 - .0240833 = \underline{.0031457}$$

Sum of squares due to A

$$= [(-.045 + .005 + .087)^2 + (.045 + .082 + .270)^2 + (.135 + .171 + .208)^2 + (.167 + .317 + .258)^2]/30 - .0240833$$

$$= (.047^2 + .397^2 + .514^2 + .742^2)/30 - .0240833 = \underline{.0084026}$$

Total sum of squares for factors A & B

$$= (.010^2 + .117^2 + \ldots + .088^2)/6 - .0240833 = 0.0125498$$

Sum of squares due to AB

$$= .0125498 - .008426 - .0025 = \underline{.0016472}$$

Total sum of squares due to E & B

$$= (.094^2 + .192^2 + \ldots + .124^2/8 - .0240833 = .006322$$

Sum of squares due to EB

$$= .006322 - .0025 - .0031457 = \underline{.000676}$$

Total sum of squares for factors A & E

$$= (-.045^2 + .005^2 + \ldots + .258^2)/10 - .0240833 = .0135672$$

Sum of squares due to AE

$$= .0135672 - .0084026 - .0031457 = \underline{.0020189}$$

Total sum of squares $= (-.015^2 + .000^2 + \ldots + .020^2)/2 - .0240833 = \underline{.0190097}$

APPENDIX 3

Given here are the details of the Multiple Linear Regression Program.

Since each cell in the experiment was made up of the sum of the distortions of two holes, each figure was divided by two to give an average value under those conditions.

The standard Multiple Linear Regression Program package of G.E. was used. There were 60 observation points and 4 variables altogether. There were 3 independent variables (degree of bend, distance of edge of hole from bend line and width of leg containing the hole) and one dependent variable (distortion). The degree of bend was taken as the tangent of the angle and the distance of the edge of the hole from the bend line and the width of the leg containing the hole in inches.

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